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Observation of ELF/VLF Electromagnetic Variations Associated with a Seismic Experimental Explosion

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Abstract. The observation and modeling of electromagnetic phenomena associated with an underground explosion are described in this paper. An experiment was performed to examine the correlation between the rock fracture and the seismogenic electromagnetic phenomena. Two sets of ELF sensors including orthogonal loop antennas and orthogonal grounding antennas were used to detect the horizontal magnetic field and horizontal electric field, respectively, and were placed at 29 and 97 m from the shot point. At just the explosion time, fast variations were detected by all of the electric field sensors, however, such a variation was not detected by the magnetic sensors even at the 29-m point. The time difference between the two separate points is within 200 μs and the variations are similar in shape but the amplitudes at 97 m are smaller than those at 29 m. Therefore, the source of the fast variations seems to be generated by the variation of the electric potential. The radial component of the electric field is relatively strong with respect to the azimuthal component of the variation and the amplitude ratio of the two remote sensors is 0.29 for the radial component. To explain the electric field variation, a buried vertical electric dipole is interpreted as a possible source model placed at the explosion depth. The dipole depth is deduced as 68 m and the dipole moment is obtained as 0.26 A·m, when the ground conductivity around the shot point is 0.01 S/m. Thus, it is shown for the first time that electromagnetic phenomena is directly related to an underground explosion by this experiment.

1. Introduction

Electromagnetic phenomena in the frequency range from ELF to HF have been observed by many researchers associated with the geological deformations such as earthquakes or volcanic eruptions[1)–5),7)]. We believe that this kind of electromagnetic phenomena can be caused by the fracture of rocks[1),2),5)]. However, the generation and the propagation mechanisms of the electromagnetic phenomena has not been clearly explained, because the direct measurement to confirm the generation mechanism and the propagation mechanism has not been performed yet. On the other hand, laboratory experiments of rock fracture have successfully demonstrated that the rock fracturing process accompanies electromagnetic phenomena in these frequency range[6)–11)]. Therefore, we believe that this kind of electromagnetic source could be a possible source of electromagnetic noise observed just before earthquakes[2),5)]. Although electromagnetic phenomena accompanies a laboratory-size of fracturing, it is not revealed that the phenomena is actually related to the natural fracturing process of earthquakes; it is not sure whether a scaling method is applicable or not. The scaling size of specimens in laboratories is usually a few tens of centimeters, while the scaling size of an earthquake can be kilometers. Furthermore, the natural fracturing process is usually tens of kilometers below the ground surface. No direct relationship in the electromagnetic phenomena between the laboratory scale of fracture and the natural scale of fracture at an earthquake has not been reported. Since it is, of course, hard to perform the direct measurement of the phenomena near a fracturing area, we must introduce a remote-sensing technique to reveal the relationship. To compare laboratory experiments with field experiments by using a remote sensing technique, it is necessary to measure the electromagnetic phenomena quantitatively.

As the scale size of artificial fracturing by using a dynamite explosion can be a few meters, we believe this kind of experiment can be used to demonstrate the missing link of the fracturing process at medium scale. Underground explosions by using a large amount of dynamite will produce a mechanical deformation of the surrounding rock by its high pressure. It is similar to the condition of the rock fracture caused by tectonic pressure. Although the time derivatives of the pressure are quite different between the two phenomena, fractures of rock can be caused if the pressure is greater than the maximum stress of the rocks. Electromagnetic phenomena can be expected at the time of an underground explosion. In fact, such electromagnetic phenomena have been detected from underground explosions[12)–15)]. In previous experiments, Yamada[13),14)] and Sakai *et al.*[15)] reported that coincidental electric potentials were generated by such explosions. However, they only showed that coincidental electric potential variations were observed prior to the arrival of the seismic wave in all of the explosions. It can easily be interpreted that an underground explosion generates electric potential around the explosion point. However the electromagnetic characteristic of the generated source or the generation mechanism is not known, because the source location and its electromagnetic parameters is not known. In the technical sense, as they had measured the electric potential by using long-span electrode pairs, they only reported that fast variations were actually observed but they could not explain whether these fast variations are actually generated by the rock fracturing process.

The main objective of this measurement is the sensing of the electromagnetic characteristic of the underground source by using sensors arranged over the ground surface. Rocks and soil covering the underground source are highly conductive compared to air that the electromagnetic field produced by the source are steeply attenuated by the covering media. As the produced electromagnetic field decreases propagating through the lossy media, a steep radial decrease of field strengths can be detected even in a short range measurement. In this experiment we introduced a new technique to fix the above unknown problem by short-span electrode pairs in seismic experimental explosions, and to take a modeling procedure in terms of calculation methods developed by Fraser-Smith *et al.*[16].

2. Observation System around the Explosion Point

The explosion seismic experiment was conducted at 01h22m JST (JST = UT + 9) on October 17, 1991 in Ohyama-cho, Toyama Prefecture (35°42′ N, 136°28′ E), to observe the crustal structure across the Central Tectonic Line by using seismic waves. The configuration of our observation systems set up around the explosion point **O** is illustrated in Fig. 1. Dynamite of 450 kg was placed at the bottom of a 75-m borehole, as shown in Fig. 1(b). The geological structure at the explosion point is also shown in Fig. 1(b). The ground surface is covered with soil down to 4 m, then gravel continues down to 17 m. The base rock at the explosion point is granite. One sensor unit, which is illustrated in the square box in Fig. 1(a), consisted of two crossed loop antennas and two pairs of 4 m-span grounding electrodes. A pair of the sensor units were used in this measurement to detect the radial dependency and the field orientation of the electromagnetic phenomena. The arrangement of the two units on the ground surface is shown in Fig. 1(a). The nearby unit **R1** is placed at 29 m from the explosion point and the remote unit **R2** is placed at 97 m on the same radial line. The two sensor units are placed along the same radial line and the other in orthogonal orientation. A grounding electrode is indicated as **G** and a loop antenna as **L**. The orientation of the sensor is indicated by the suffix **r** for radial and by **a** for azimuthal. The electrode was a carbon-coated steel 30 cm in length and 1 cm in diameter. The potential difference between a pair of electrodes was amplified by a high-input-impedance differential amplifier operated by batteries and its output was transmitted to a recorder located approximately 150 m from the explosion point through coaxial cables. The magnetic field was measured by a ferrite-cored loop antenna with the dimension of 30 cm in length and 1 cm in diameter, and with 1000 turns of 0.5 mm dia. copper wire. The output of the loop antenna was amplified by a low-input-impedance amplifier and also transmitted to the recorder. The setup of the remote sensor unit at **R2** was completely the same as the unit at **R1**. The output pairs of the same orientation but different in distance were recorded on the same DAT recorder to eliminate ambiguities in time difference. The alignment of the tape was made using atmospheric waveforms. The ambiguity in the time scale is approximately 200 μs among them. The frequency responses of these measurement systems were flat within 3 dB from 10 Hz to 5 kHz. Recording was started 50 min before the explosion and stopped 20 min after it. Seven outputs of the sensor system were recorded at a normal level, however, the output of the azimuthal magnetic sensor at **R1** was not functioning properly during this period. The recorded digital data was transferred to a personal computer with a magneto-optical disk, and was analyzed by software.

3. Observation Results

The potential differences of the electrode pairs are converted to the surface electric field strength and are shown in the upper two panels of Fig. 2. The electric field strength with the same orientation is shown in the same panel to compare the time difference between the two separate sensors. In the same manner, the magnetic field strength is shown in the lower two panels of Fig. 2. It is very clear that electric field variations start with just the same timing as the explosion at the two separate positions and on the two orientations. The amplitude of the electric field at the distant point **R2** is smaller than that at **R1**. However, the phase is almost the same at the two points. The initial potential variations even at 29 m cannot be attributed to the arrival of the acoustic or the seismic wave, because the deduced propagation speed of the fast variation is much faster than that of the seismic wave and of the acoustic wave. Note that the magnetic field data are contaminated by the field induced by electric power transmission lines close to the explosion point. The waveforms of the initial 20-ms interval from the explosion time are shown in Fig. 3. The undesired spectral components caused by the induction from the power lines have already been filtered out. The trace of a relatively large amplitude in each panel in Fig. 3 is the record at 29 m and the other at 97 m. However, no coincidental variation can be identified from

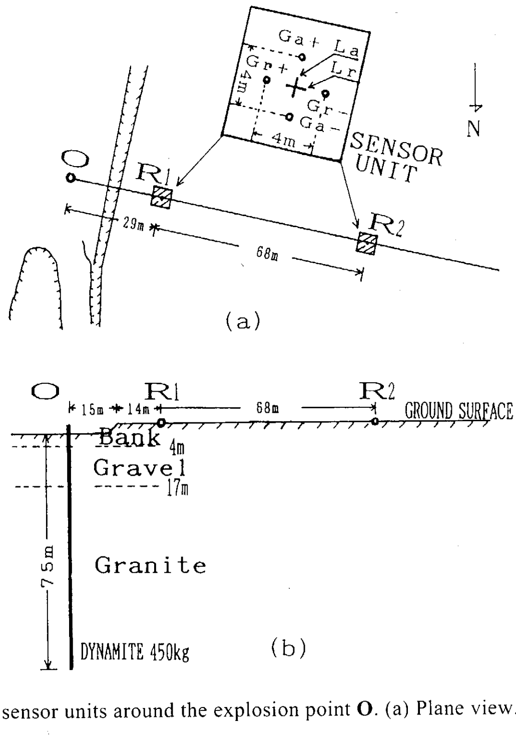

Fig. 1. Setup of sensor units around the explosion point **O**. (a) Plane view. (b) Lateral view.

the magnetic field records shown at the lower two panels in Fig. 2. The radial component of the electric field is four times stronger than the azimuthal component, and the shape of the waveform at the two separate locations are quite similar, as seen in Fig. 2. It is interesting to note that the fast variation starts just at the time of the explosion but are terminated at approximately 10 ms after the trigger of the explosion. No remarkable fast variation can be seen after 10 ms.

In Fig. 4, the radial amplitudes of the two separate points at 29 and 97 m, as shown in the top panel of Fig. 2, is plotted in the x-y coordinates for the period of 10

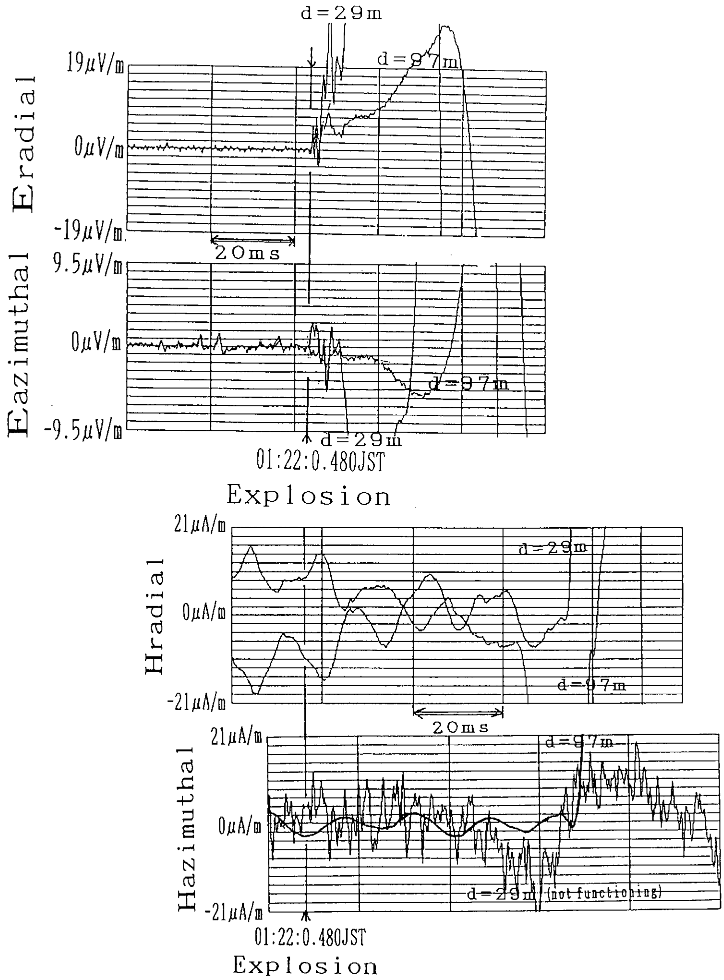

Fig. 2. Electric and magnetic fields measured at two separate points, **R1** and **R2**, on the ground surface. E-fields started their variations at just the same time of the explosion. Unfortunately the azimuthal sensor at 29 m did not function properly during this observation. Note that the magnetic components were remarkably disturbed by the induction field from a power line.

ms from the explosion time. The movement of the resulting vector locus indicates the relationship between two components. As the trace of the two electric field vectors moves along the straight broken lines, it is interpreted that the radial components of the electric field variations at the two separate sensors show a good correlation and indicate the constant amplitude ratio of 0.29 which is obtained by the gradient of the straight line. On the other hand, the spectra of the initial 10 ms variations at 29 m which are shown in Fig. 3 are displayed in Fig. 5. Both spectra show the broad peak at 750 Hz. Note that the gradual increase below 250 Hz is due to the abrupt increase in amplitude at the explosion time. Therefore, the characteristic frequency of the observed variation at 750 Hz is assumed as the transmission frequency of the generation source in the next modeling procedure. Since the semi-periodic variation can be considered as a main component of the variation based on the above spectral analysis, the time difference between the two waveforms in Fig. 3 is within 0.2 ms and is interpreted as a phase difference of within 30 deg.

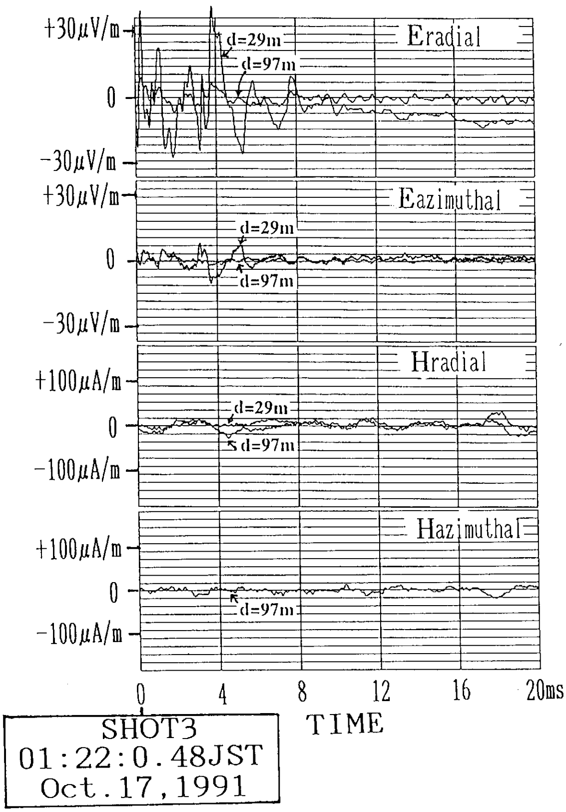

Fig. 3. Waveforms of the initial 20-ms interval from the explosion time. The trace of a relatively large amplitude in each panel was observed at 29 m. The undesired spectral components caused by induction from the power lines have already been filtered out.

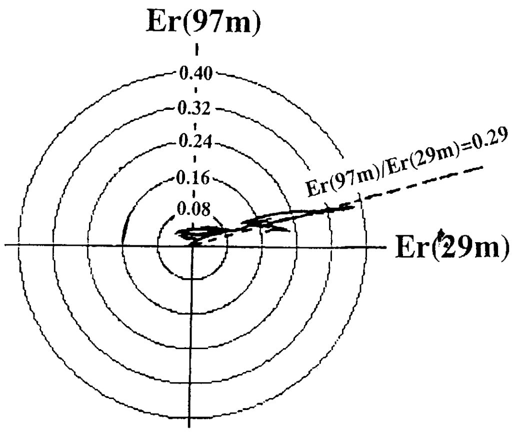

Fig. 4. Vector trace of the radial components observed at the two separate points. The trace seems to align the broken line which indicates a constant amplitude ratio of 0.29.

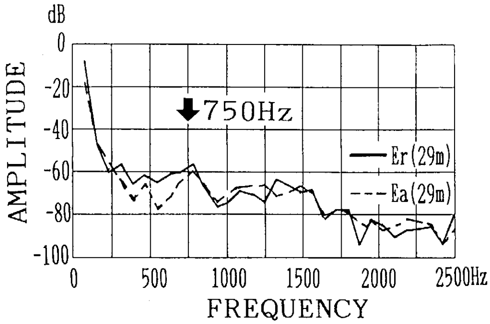

Fig. 5. Spectral amplitude of the electric field variations at 29 m for the 10-ms period after the explosion time, as shown in Fig. 3.

4. Modeling the Source

The radial decay of the amplitude of the electric field and the excess of the electric field relative to the magnetic field can be attributed to a source like an electric dipole. Based on our observation, the radial component is dominant at both points, 29 and 97 m, the amplitude ratio of the radial component at the two distance is 0.29, and the phase difference at 750 Hz is within 30 deg. These characteristics should be used as the key parameters in the following model calculation.

It is assumed in the models that an electric dipole should be placed under the ground surface. The ground conductivity around the explosion point is not known in detail but the apparent resistivity deduced by the VLF-MT technique was 10 to 100

Ω·m. Therefore, we first assume that the ground can be considered as a homogeneous medium whose conductivity is 0.01 S/m and whose relative permittivity is 10. The model calculation is performed at the characteristic frequency of 750 Hz using a submerged dipole in terms of the formulation of Fraser-Smith *et al.*[16]. The calculation is made for vertical and horizontal electric dipoles placed under the ground.

At first, the radial and the azimuthal electric field strength and the azimuthal magnetic field strength, and their relative phase angles on the ground surface are calculated along the horizontal distance up to 200 m from the location of the dipole. An example of the horizontal variation of the calculated fields and their phase angles for the vertical dipole depth of 70 m is shown in Fig 6. The calculated electric and magnetic field strengths are normalized to the dipole moment of **p**. No azimuthal field can be expected theoretically for the vertical dipole. Although an azimuthal component can be expected for the horizontal electric dipole, the expected magnetic field strength relative to the electric field must be much larger than the noise threshold of this measurement. Thus, we conclude that the main source of the electromagnetic fields should be attributed to a vertical electric dipole.

Secondly, calculation is made to explain the ratio of Er(97)/Er(29) = 0.29 and their relative phase difference within 30 deg. Figure 7(a) shows the ratio with respect to the dipole depth and Fig. 7(b) shows their relative phase angle. It is interesting to note that the ratio is quite variable for a shallow dipole down to 10 m-depth and that it gradually increases with depth. It can be seen from Fig. 7(a) that the ratio meets

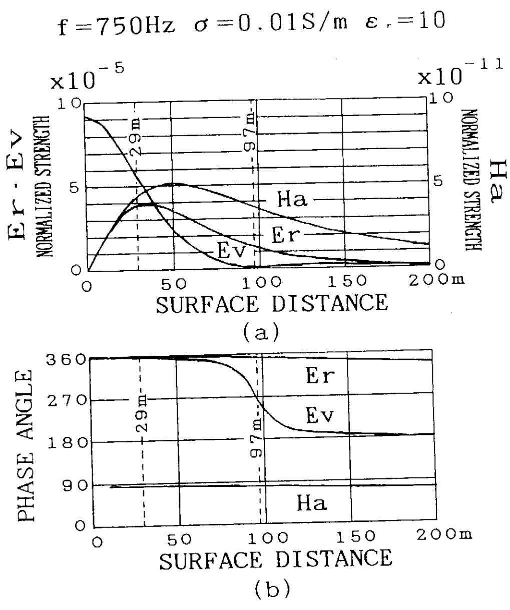

Fig. 6. Horizontal variation of amplitudes and phases induced by a vertical electric dipole. The surface distances of 29 m and 97 m are indicated by the vertical broken lines.

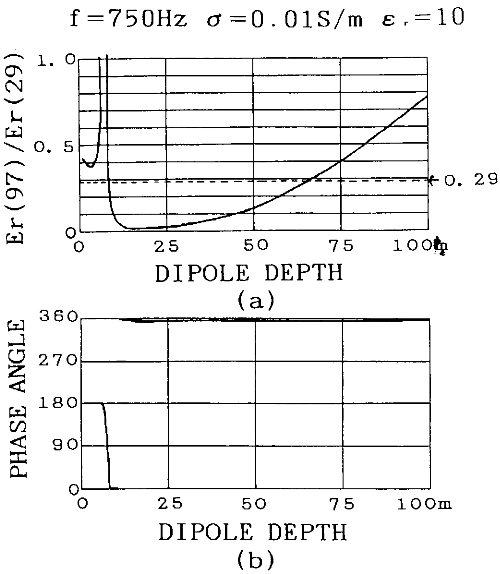

Fig. 7. Vertical variation of the amplitude ratio and the relative phase of the radial components for a ground conductivity of 0.01 S/m. The observed amplitude ratio of 0.29 is shown by the horizontal broken line. The curve of the amplitude ratio crosses at two depths.

at two depths with the value of 0.29 which has been measured by this experiment. The two depths are 8 m and 68 m. The relative phase angles at these depths are 0 deg and 5 deg, respectively. Therefore, the two dipole depths are possible locations to produce the measured electromagnetic fields.

Although one of the possible sources can be placed at the 8-m depth, it is relatively displaced from the actual exploding depth of approximately 70 m. Therefore, if the shallow source generated the observed field, some excitation process due to the explosion must be included in the generation process. As the starting time of the variation is coincidental within 200 μs, the excitation process must propagate 62 m within 200 μs. Then, the propagation speed should be more than 310 km/s. The speed is much faster than the seismic or the acoustic waves in rocks. It is, therefore, impossible to excite the shallower source through the seismic or acoustic waves. On the other hand, as the depth of 68 m can be easily related to the depth of the dynamite explosion, no propagation delay is necessary in the physical excitation. Therefore, it is concluded that the deep source at 68 m can generate the observed variations. The pressure of the explosion should be enough to make the surrounding rocks fracture[14),15)]. Hence, it is clear that the observed electromagnetic variation is excited by the explosion. However, it is necessary to investigate quantitatively whether the deduced electric dipole can be generated by the rock fractures.

The dipole moment **p** can be obtained by dividing the measured radial electric field strength by the normalized one shown in Fig. 6 for the depth of 68 m. The dipole moment is 0.26 A·m. By using these deduced dipole moments, the expected magnetic field strength at 29 m can be calculated as 1.2×10^{-11} A/m for the 68-m depth. The expected magnetic field strength is much smaller than the measurable strength of 1.0×10^{-7} A/m of the magnetic sensors. It is, therefore, consistent with the fact that no magnetic field variation was observed at the same time as the explosion.

5. Conclusions

The coincidental variations of the electric fields were measured on the ground surface close to the underground explosion point. The variations are coherent between the two separate points and show a radial decrease in amplitude. To explain these measured characteristics of an electromagnetic source generated by the underground explosion, model calculations for submerged vertical and horizontal electric dipoles were made. As the result of these calculations, a vertical electric dipole placed at depths of 8 m or 68 m are possible electromagnetic sources of the explosion. However, according to the observed time sequence of the variations, it is found that the deeper source possibly generates the observed variations. Using the deduced dipole moment at the two depths, it is concluded that the expected magnetic field strength must be much lower than the measurable strength. This is the first time to obtain the electric characteristics of an explosion and to relate the electromagnetic phenomena to the location of the explosion. Although the typical characteristics can be explained by the simple vertical dipole model, it is required to perform more calculations and to interpret a physical model, in order to explain other characteristics measured in this experiment.

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REFERENCES

(1) Gokhberg, M. B., Morgounov, V. A., Yoshino, T. and Tomizawa, I. (1982): *J. Geophys. Res.*, **87**, 7824–7828.
(2) Yoshino, T., Tomizawa, I. and Shibata, T. (1985): *Ann. Géophys.*, **3**, 727–730.
(3) Parrot, M., Lefeuvre, F., Corcuff, Y. and Goderoy, P. (1985): *Ann. Géophys.*, **3**, 731–736.
(4) Oike, K. and Ogawa, T. (1986): *J. Geomagn. Geoelectr.*, **38**, 1031–1040.
(5) Yoshino, T. and Tomizawa, I. (1990): *J. Geomagn. Geoelectr.*, **22**, 225–235.
(6) Nitsan, U. (1977): *Geophys. Res. Lett.*, **4**, 333–336.
(7) Warwick, J. W., Stoker, C. and Meyer, T. R. (1982): *J. Geophys. Res.*, **87**, 2851–2859.
(8) Yamada, I. and Masuda, K. (1985): *CA Kenkyukai*, *'85*, 129–135 (in Japanese).
(9) Ogawa, T., Oike, K. and Miura, T. (1985): *J. Geophys. Res.*, **90**, 5245–5249.
(10) Schloessin, H. H. (1985): *Ann. Géophys.*, **3**, 709–720.
(11) Cress, G. O., Brady, B. T. and Rowell, G. A. (1987): *Geophys. Res. Lett.*, **17**, 1465–1468.

(12) Yamada, I. and Murakami, H. (1982): *Jishin*, **35**, 393–400 (in Japanese).
(13) Yamada, I. (1989): Ph.D. Thesis, Nagoya University.
(14) Yamada, I. (1990): *CA Kenkyukai, '90*, 39–48 (in Japanese).
(15) Sakai, H., Oda, H., Nakayama, T. and Doi, H. (1992): *J. Phys. Earth*, **40**, 447–458.
(16) Fraser-Smith, A. C., Bubenik, D. M. and Villard, O. G., Jr. (1987): *Radio Sci.*, **22**, 567–577.